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COST ESTIMATES OF CONCENTRATED PHOTOVOLTAIC HEAT SINK PRODUCTION

June 2016

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The focus of the thesis is the formulation of a credible, reasonable, and professionally developed cost analysis of adding optimized cooling technologies to concentrated photovoltaic (CPV) systems. Current CPV systems use basic heat sink designs to increase efficiency. Modern heat sink design can achieve greater overall efficiencies of electricity generation. As the CPV market has matured, production costs have come down to near flat-panel photovoltaic (PV) production costs. CPV units outperform flat-panel PV units in areas of high direct normal irradiance (DNI) in terms of electricity generation efficiency and power produced per square meter. Gains in efficiency should shorten payback periods for CPV systems, if they are not prohibited by high upfront costs of manufacturing and installation. Ultimately, a better understanding of cost drivers in CPV unit production will help in the making of a more informed selection of optimal technology for Department of Defense/Department of the Navy self-sufficient solar power for our bases. This research will help further U.S. Navy energy goals by increasing alternative energy ashore and its use across the Navy.

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COST ESTIMATES OF CONCENTRATED PHOTOVOLTAIC HEAT SINK PRODUCTION

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Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

The focus of the thesis is the formulation of a credible, reasonable, and professionally developed cost analysis of adding optimized cooling technologies to concentrated photovoltaic (CPV) systems. Current CPV systems use basic heat sink designs to increase efficiency. Modern heat sink design can achieve greater overall efficiencies of electricity generation. As the CPV market has matured, production costs have come down to near flat-panel photovoltaic (PV) production costs. CPV units outperform flat-panel PV units in areas of high direct normal irradiance (DNI) in terms of electricity generation efficiency and power produced per square meter. Gains in efficiency should shorten payback periods for CPV systems, if they are not prohibited by high upfront costs of manufacturing and installation. Ultimately, a better understanding of cost drivers in CPV unit production will help in the making of a more informed selection of optimal technology for Department of Defense/Department of the Navy self-sufficient solar power for our bases. This research will help further U.S. Navy energy goals by increasing alternative energy ashore and its use across the Navy.

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LIST OF ACRONYMS AND ABBREVIATIONS

CPV   concentrated photovoltaics

DNI   direct normal irradiance

DOD   Department of Defense

DON   Department of the Navy

kW   kilowatts

kWh   kilowatt hours

LCOE   levelized cost of energy (electricity)

NPV   net present value

NSAM   Naval Support Activity Monterey

^{o}C   degrees Celsius

Payback   time period for a capital investment to recoup initial cost

PG&E   Pacific Gas and Electric

PV   photovoltaics

SECNAV   Secretary of the Navy

W   watts

η efficiency, %

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I. INTRODUCTION

A. DEPARTMENT OF THE NAVY GOALS

The Department of Defense remains the largest single consumer of energy in the Unites States, consuming 80% of the federal government's energy (DASN, 2012). The Department of the Navy (DON) exhausts 28% of DOD's operational and shore energy. The DON shore-based footprint is substantial, with over 102 installations consisting of over 90,000 buildings, amounting to more than 663 million square feet (DASN, 2012).

The DON energy goals set by Secretary Ray Mabus in 2009 have not changed and are depicted in Figure 1.

1. Increase Alternative Energy Use DON-Wide	By 2020, 50% of total DON energy consumption will come from alternative sources.
2. Increase Alternative Energy Ashore	By 2020, DON will produce at least 50% of shore based energy requirements from alternative sources; 50% of DON installations will be net-zero.
3. Reduce Non-Tactical Petroleum Use	By 2015, DON will reduce petroleum use in the commercial vehicle fleet by 50%.
4. Sail the "Great Green Fleet"	DON will demonstrate a Green Strike Group in local operations by 2012 and sail it by 2016.
5. Energy Efficient Acquisition	Evaluation of energy factors will be mandatory when awarding contracts for systems and buildings.

Figure 1. The Secretary of the Navy's Energy Goals. Source: DASN (2012).

One of the five goals is that by 2020, the DON will produce at least 50% of shore-based energy requirements from alternative sources and that 50% of DON installations will be net zero (DASN, 2012). From the DOD perspective, "A net zero energy military installation produces as much energy on-site from renewable energy generation or through the on-site use of renewable fuels, as it consumes in its buildings, facilities, and fleet vehicles" (Booth, 2010, p. 5). Such goals and other initiatives from federal

authorities combine to meet the overall requirement to "provide secure, reliable, and affordable energy to the United States Navy and Marine Corps" (DASN, 2012, p. 2). Such a goal is two-fold. Producing 50% of shore-based energy requirements from alternative sources requires defining the current shore-based energy requirement. Net zero buildings and energy conservation practices reduce the overall energy requirements for shore-based facilities. Therefore, the Navy's strategy is attacking this goal from two sides: reducing the energy requirement and fulfilling 50% of the new requirement with alternatively sourced energy. These goals work together such that the energy requirement in 2020 will be less than the current energy requirement as alternatively sourced energy capacity expands.

B.   SOLAR IS A VIABLE OPTION

While DON is considering a full portfolio of renewable energy technologies, solar technologies offer mature solutions that are compatible with the missions of most installations. Ground-based photovoltaic (PV) offers opportunities for large-scale electricity generation, and rooftop PV offers smaller-scale solutions that can be installed almost anywhere. DON installations in the Southwestern U.S. and Hawaii are particularly good locations for solar generation, as they are exposed to steady year-round sunshine and in many cases high levels of direct normal irradiance (DNI). Beyond traditional PV, some climates favor rooftop solar water heating, but the majority of installed solar systems, are PV (EIA, 2015).

Solar power generation has great benefits for the DON considering the abundance of a free, reliable fuel source (sunlight) at many DON installations. The two primary issues holding back more widespread use include capital costs and intermittency (DASN, 2012). While the price per kWh of solar is falling as the solar market continues to mature, solar installation involves relatively high upfront costs compared to hooking up to the existing grid infrastructure (GTM Research, SEIA, 2015). Multiple factors can justify this additional cost ranging from environmental concerns and energy independence/security to the eventual payback of the installation cost and money saved by paying utility companies less. Intermittency refers to the fact that sun does not shine on a fixed location

24 hours a day, seven days a week. Therefore, installations must have other options to satisfy demand during periods of darkness or less than required sunlight. Peak hours of electricity demand may shift for different installations, but typical demand peaks in the late afternoon/early evening, which is the same time that solar generation wanes to zero for the evening. Therefore, storage solutions are needed to maximize the benefits of solar generation or an alternate energy source (grid, wind, thermal) is needed to satisfy demand during solar intermittency.

C.   WHY CPV?

One way to maximize solar generation is to use high-efficiency photovoltaic cells. Given a limited window of opportunity to produce electricity, solar systems must be scaled to capture as much sunlight as possible through sheer numbers or the systems in use must convert sunlight to electricity as efficiently as possible.

Currently, the most efficient solar cells are multi-junction cells based on group III-IV compound semiconductor materials. The most recent record achieved, a lab tested, 46% efficiency with a four junction solar cell was developed jointly by Soitec, CEA-Leti, France, and Fraunhofer ISE (Fraunhofer, 2014). Multi-junction cells are very efficient, but more costly to produce. Thus, they are primarily used in concentrated photovoltaic (CPV) systems. CPV systems concentrate and focus sunlight onto a smaller focal point in order to take advantage of the highly efficient solar cells.

Generally, PV systems use silicon-based solar cells with efficiencies less (current max of 27.6%) than the multi-junction solar cells used in CPV systems (NREL 2016). The higher efficiency cells used in CPV systems allows a higher energy density per square meter than traditional PV in locations with high DNI. Therefore, if land use is a priority (high value per acre) CPV may have advantages to PV at select installations.

D.   HEAT SINKS FOR CPV

CPV systems have many areas of improvement that can lower Levelized Cost of Electricity (LCOE). Overall system efficiency can be improved by targeting losses in sunlight focusing/concentrating, solar cell efficiencies, electrical loss due to resistance, and inverter efficiencies. Of these, the most dramatic improvements continue to occur in solar cell efficiencies, which drive all other efficiency levels except for optical.

Solar cell efficiency decreases as temperature increases in a linear relationship. Therefore, the cooler a solar cell can be kept the greater the gains in efficiency (Skoplaki, 2009). This phenomenon, while not as prevalent in multi-junction solar cells as Silicon, exists for all solar cells. Thus, with all other variables held constant, a solar module operating in a cooler climate enjoys greater efficiency than the same module in a hotter climate. With this principle in mind, greater solar cell efficiency can be achieved by cooling the cell, regardless of cell type.

Cooling methods can be broken down into two main categories, active and passive. Active systems involve circulating cooler air or water near a module to dissipate heat more quickly than ambient conditions would. A major drawback to active cooling is that an energy source is required to power the cooling system and that either draws from the solar module, reducing usable output, or requires an alternate source of energy (grid, generator, batteries). In contrast, passive cooling can be as simple as raising a solar panel away from a surface (like a roof) enough to allow more airflow around the system or by attaching fabricated heat sinks to the back of solar panels to further dissipate heat into ambient airflow. Traditional heat sinks include a flat aluminum back plate that simply is part of the CPV unit housing or can include heat dissipating extrusion designs like pin fins or radial fan designs. Figures 2 and 3 are examples of both designs.
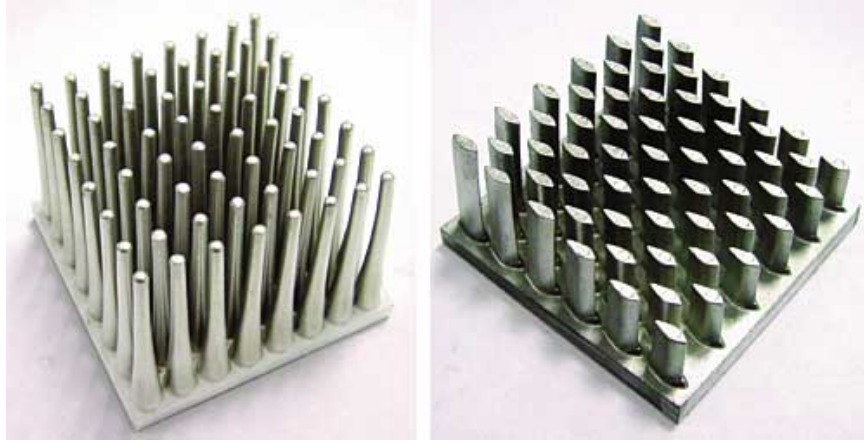
Figure 2. Pin Fin Heat Sink. Source: Johnson (2004).

Figure 3. Radial Heat Sink. Source: Blumenfeld, Foresi, Lang,
and Nagyvary (2010).

An advantage of a passive heat sink design is that better efficiency may be achieved with existing solar cells at a relatively low cost. The primary aim of this research is to determine whether adding complex or modern heat sinks to CPV systems is a prudent decision with regard cost. Simply put, is adding a complex or modern heat sink to a CPV system a sound business decision?

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II. BACKGROUND

A. ELECTRICITY FROM THE SUN

Photovoltaic technology−generating electricity directly from sunlight—has origins in the initial discovery of the photovoltaic effect by Edmond Becquerel in France in 1839. Not much changed in the first 100 years, but 1954 has been christened as the start of the modern photovoltaic age. That year, Bell Telephone and RCA laboratories reported new types of semiconductors, based on silicon and germanium, which were significantly more efficient than previously known materials (Lynn, 2010). The space race that followed between the U.S. and Soviet Union catalyzed research and development for solar powered satellites. Beyond space-based solar, the prime driver for practical terrestrial applications has been cost. Reduced cost of material, production learning curves, new technology breakthroughs, and government incentives have brought the total costs associated with producing photovoltaic systems down considerably since the 1950s. Such developments along with an increasing awareness of the environmental impacts of fossil fuel-based electricity generation have opened large inroads of practical applications of solar electricity generation.

Compared to other electricity generation methods—fossil or nuclear fuel based thermodynamic cycles, hydro-electric, or wind—solar remains elegant in its simplicity. A solar cell converts sunlight directly into electricity without moving parts, additional fuel, or waste products (Lynn, 2010, p. 11). A photovoltaic cell simply takes photons in and out come electrons. While this process is simplistic, the research and development required to achieve such processes along with rigid manufacturing requirements, has been and is quite complex. Manufacturing thin layers of semi-conductor materials for photovoltaics requires the (sometimes rare) elements for such materials and high levels of precision and cleanliness similar to the computer and electronics industry (Lynn, 2010, p. 12).

Beyond the basic physics and chemistry associated with the photovoltaic process, consumers care about efficiency. Solar efficiency represents how much electricity is

produced in the photovoltaic process compared to the input (light/photons) received by the solar cell (i.e., a ratio of output to input). Figure 4 is a graphical depiction of solar cell technologies and their respective lab tested efficiencies from late 1970s to 2016. Five categories of photovoltaic technologies are depicted and color coded.
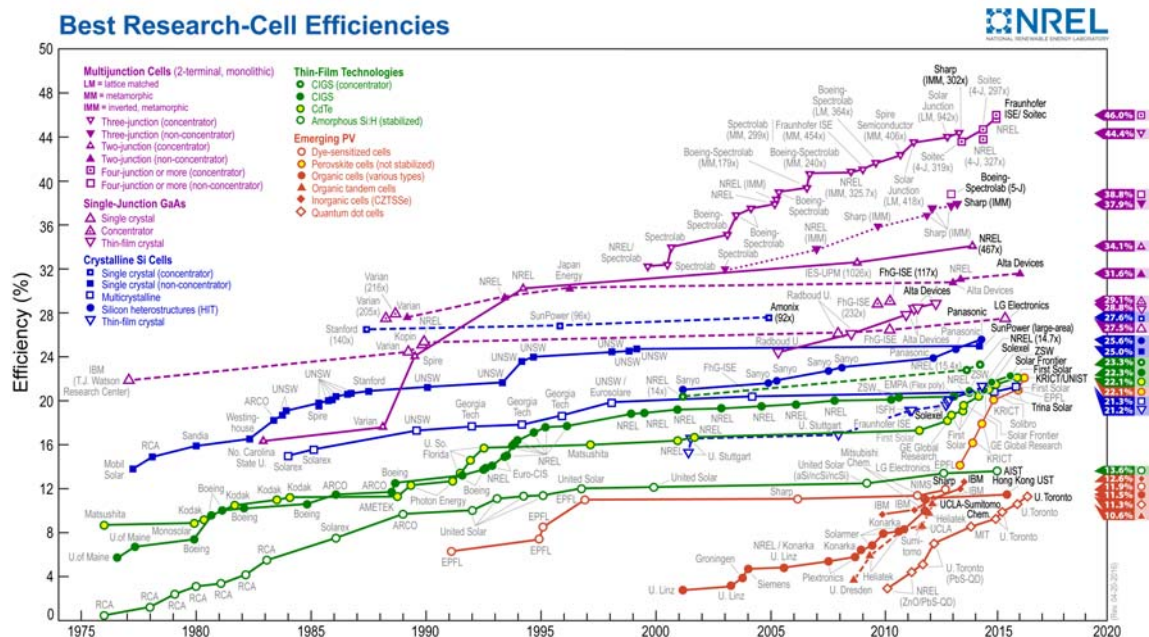
Figure 4. Solar Cell Efficiencies. Source: NREL (2016).

The least efficient to the highest are as follows: emerging PV, thin-film technologies, crystalline silicon cells, single-junction gallium arsenide, and multi-junction cells. Most PV, due to price and availability, relies on some form of silicon-based solar cells. While a slight upward trend exists, silicon efficiencies have leveled off since the late 1990s and maxed out at 25.6% non-concentrator and 27.6% with concentrator. The most remarkable recent growth is in multi-junction cells that have displayed the highest levels of efficiencies since the late 1980s but have taken off since the late 1990s/early 2000s and achieved a max lab tested efficiency of 46%. As the number of junctions increase with or without concentrator, the overall complexity of the solar cell increases. With greater complexity comes greater cost. CPV systems use a much smaller cell than flat-plate technology and are currently the best terrestrial systems

to take advantage of the higher efficiencies gained from the most efficient multi-junction cells.

B.   CPV BASICS

The backbone of any PV or CPV system is the solar cell. The solar cell is the actual material that converts sunlight to electricity. Solar cells in PV applications are typically made of silicon and cells in CPV applications are typically group III/IV multi-junction elements such as gallium arsenide. CPV units consist of some sort of concentrator, solar cell, heat sink, and a structural housing for the components. The units can be designed in multiple ways, but typically use either refractive or reflective designs for concentration. Figures 5 and 6 represent the basic layout of both CPV designs.
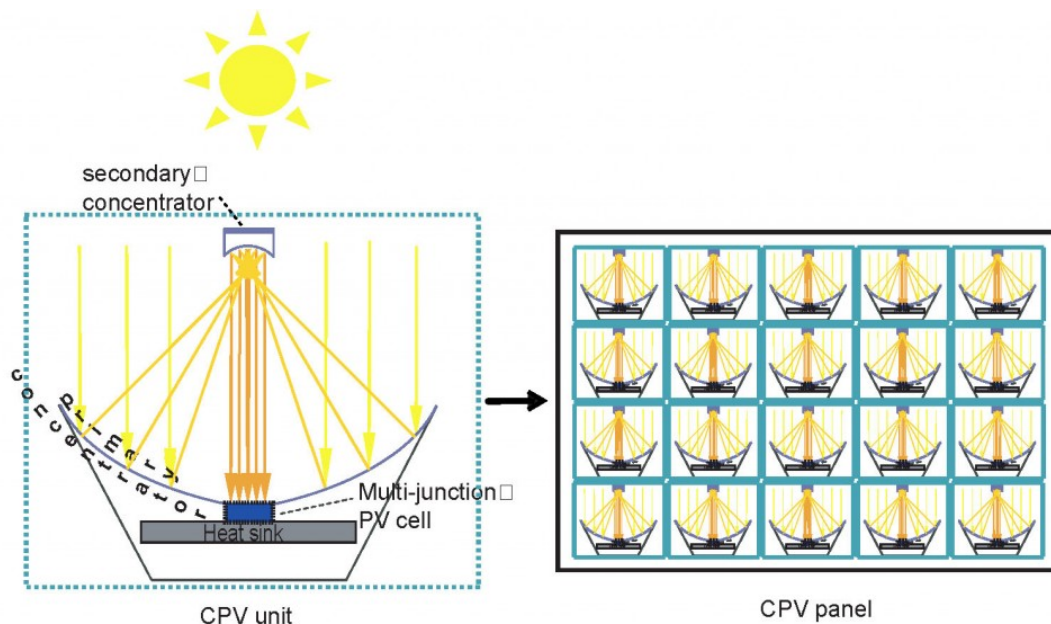
Figure 5. Reflective CPV. Source: CPV Systems (2012).
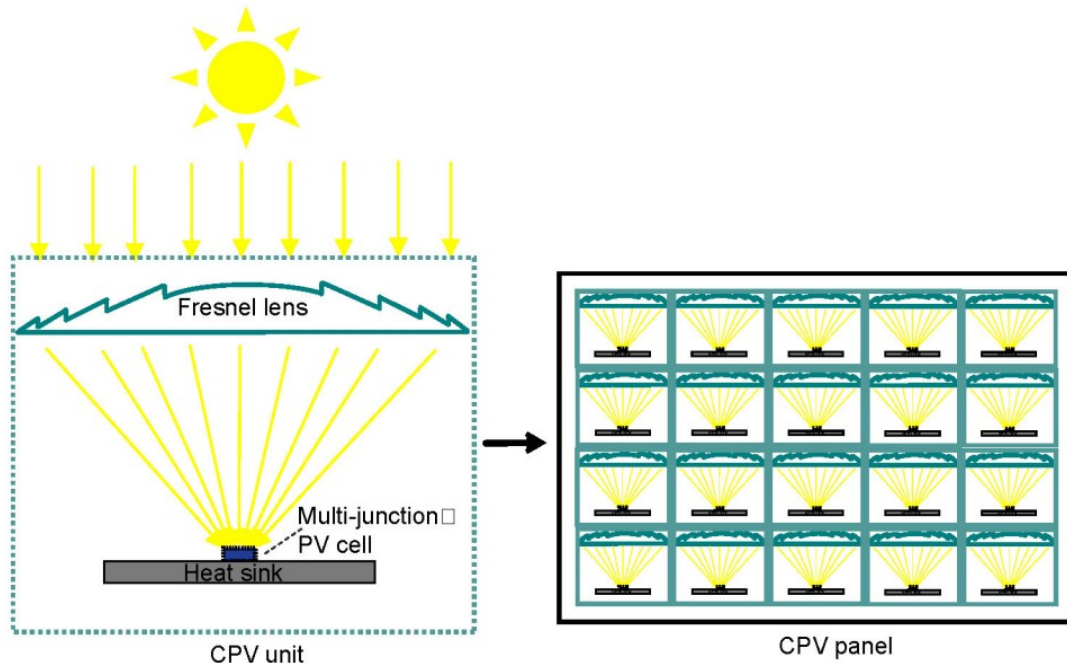
Figure 6. Refractive CPV. Source: CPV Systems (2012).

Reflective units (Figure 4) are typically larger than refractive (Figure 5) due to the use of a primary parabolic concentrator and a secondary concentrator. Also, reflective units and their respective solar cell may consist of a panel of multiple solar cells instead of a single solar cell used in refractive designs. Both designs capture and direct sunlight onto small multi-junction solar cell(s). The solar cell typically has some sort of heat sink attached to dissipate the hotter temperatures realized from concentrated sunlight. Each individual unit can then be grouped together to create a CPV panel or module that combines the electricity generated from the PV reaction in each unit.

CPV technology ranges from small to utility scale options for the generation of solar electricity. CPV market share is small compared to PV, mainly due to competition with PV prices and the challenge of raising enough capital to scale up CPV operations (Phillips, Bett, Horowitz, Kurtz, 2015). In a more promising light, CPV systems continue to achieve higher efficiencies than what is possible for PV systems with room for future improvement. Such improvements increase overall system returns on investment and

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provide pathways for further reduction in system costs (Phillips et al., 2015). Phillips et al. (2015) notes:

> The key principle of CPV is the use of cost-efficient concentrating optics that dramatically reduces the cell area, allowing the use of more expensive, high-efficiency cells and potentially a levelized cost of electricity (LCOE) competitive with Concentrated Solar Power and standard flat-plate PV technology in certain sunny areas with high Direct Normal Irradiance (DNI). (p. 1)

CPV systems are typically classified by concentration levels. As of the end of July 2015, more than 90% of publicly documented installed capacity was high concentration photovoltaic (HCPV) with dual axis tracking (Phillips et al., 2015). Concentrating sunlight by a factor of 300–1000x allows the use of smaller, highly efficient multi-junction solar cells that are also more expensive than crystalline silicon (Phillips et al., 2015). Table 1 classifies what is considered HCPV or low concentration photovoltaic LCPV, tracking method required, and solar cell type used to convert sunlight to electricity. All future references to CPV in this thesis imply HCPV unless otherwise stated.

Table 1.   Description of CPV Classes. Adapted from Phillips et al. (2015).

Class of CPV	Typical concentration ratio	Tracking	Type of converter
High Concentration PV (HCPV)	300-1000	Two-axis	III-V multi-junction solar cells
Low Concentration PV (LCPV)	< 100	One or two-axis	c-Si or other cells

The tradeoff is in the amount of cell area required to produce similar amounts of electricity. By focusing and concentrating sunlight onto a small cell area, much less multi-junction material is required compared to the silicon cell area required to produce the same amount of electricity. Therefore, CPV systems can afford the expense of exotic multi-junction cells due to their high relative energy density (electricity generated per square inch of cell area). Figure 7 illustrates the comparative difference of solar cell size between Si cells and a multijunction solar cell that achieves the same output.
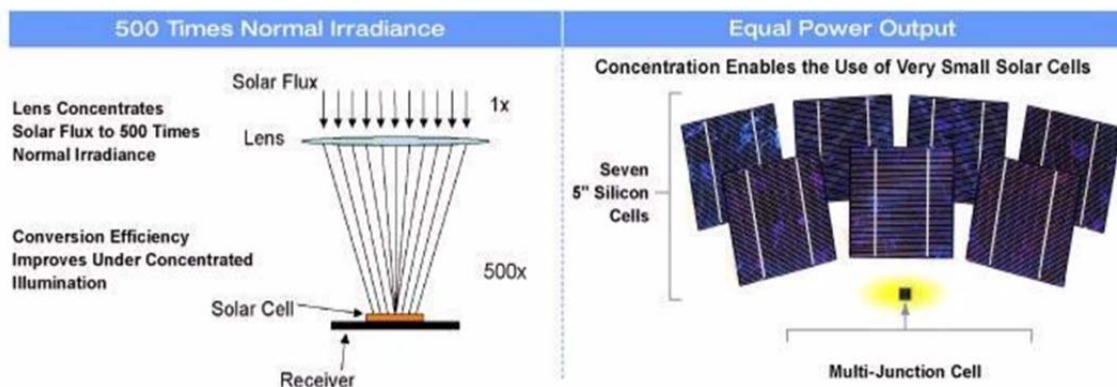
Figure 7. CPV/Silicon Flat Panel Comparison. Source: Rozwoj (2016).

Greater energy density from the solar cell translates well to the overall size of CPV units and corresponding CPV arrays. In areas where available land is scarce or prohibitively expensive, CPV can greatly reduce area-related system costs.

C.   TRACKING

Another key aspect of CPV is that CPV requires direct sunlight and therefore must be tracked. DNI referenced earlier, is the "direct irradiance received on a plane normal (perpendicular) to the sun over the total solar spectrum" (P. Blanc et al. 2014, p. 562). Tracking systems must be used to keep the plane of solar modules normal to the path of the sun across the sky.

Annual cloud coverage or any other atmospheric phenomena that may absorb or diffuse incoming solar radiation directly reduces DNI for a given area. Diffuse sunlight cannot be efficiently concentrated, so the optics used in concentration need direct

sunlight in order to focus sunlight onto a small surface. CPV or other concentrator systems, perform best in areas of high DNI.

Tracking modules come in two general varieties; single axis or dual axis, with slight variations of either variety. Figure 8 illustrates two versions of each variety.
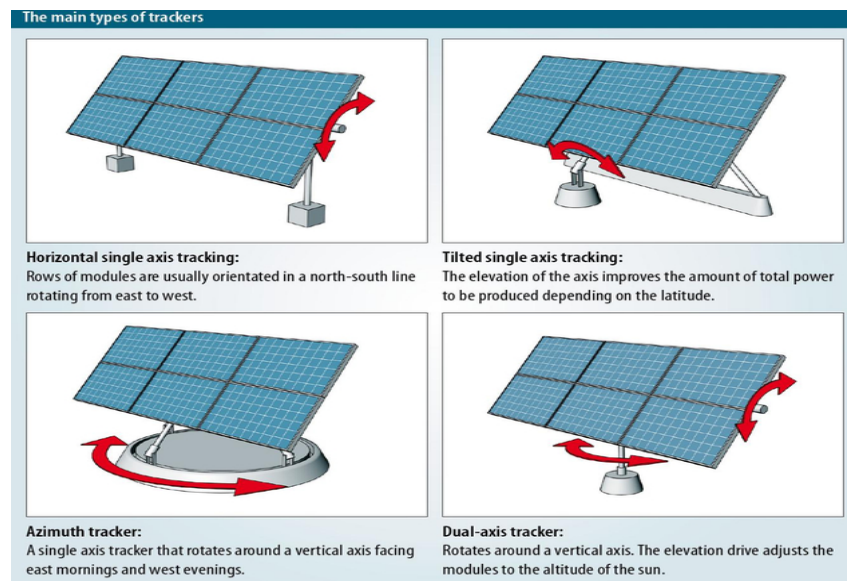
Figure 8. Tracker Types. Source: Nithya (2015).

Dual axis, while more complex than single axis, can more accurately follow the sun's path throughout the day offering more direct sunlight for a longer period of time to the respective system's solar cell. Single axis systems are fixed in one axis and track the sun in general from east to west. Single axis does not account for the seasonal north/south shift in the elevation of the sun's arc across the sky and is typically set to the midpoint between the elevation shifts. Usage of this midpoint incurs losses when not pointed directly at the sun. Dual axis offers the most accurate tracking as it can adjust for east–west and north–south movement of the sun. While installation and maintenance costs are higher than a fixed tilt array or single axis, dual axis tracking allows higher energy production throughout the day in sunny regions. Figure 9 shows this relationship.

The power curve for any PV array mounted on a tracker is broader than that for a fixed array, and thus is deemed to add better shoulders to the curve. This figure shows the relative power curves for flat-plate PV mounted at a fixed tilt, flat-plate PV mounted on single-axis trackers and Amonix concentrated PV mounted on dual-axis trackers.
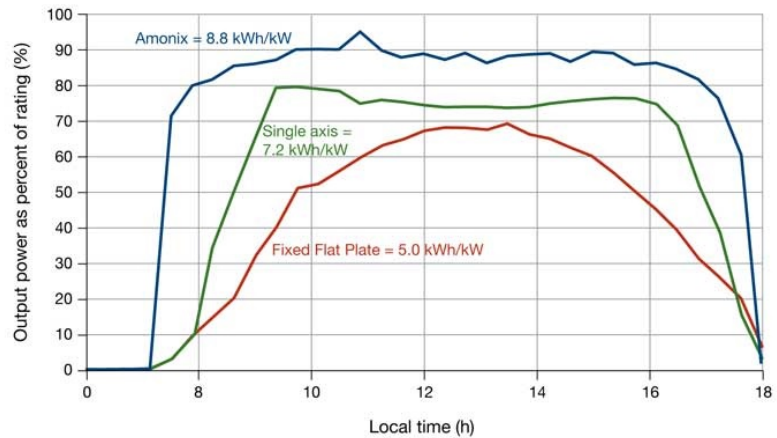
Figure 9. Relative Power Curves. Source: Smith (2011).

Of particular importance is the energy produced later in the day closer to peak consumption times. In areas where time of use (TOU) rates are used by electricity providers, energy produced during peak demand times is more valuable.

Beyond the issues already discussed, Figure 10 highlights strengths and weaknesses regarding CPV systems as compared with traditional flat-plate PV.

CPV Strengths	CPV Weaknesses
High efficiencies for direct-normal irradiance	HCPV cannot utilize diffuse radiation LCPV can only utilize a fraction of diffuse radiation
Low temperature coefficients	Tracking with sufficient accuracy and reliability is required
No cooling water required for passively cooled systems (as is required for CSP)	May require frequent cleaning to mitigate soiling losses, depending on the site
Additional use of waste heat possible for systems with active cooling possible (e.g. large mirror systems)	Limited market – can only be used in regions with high DNI, cannot be easily installed on rooftops
Modular – kW to GW scale	Strong cost decrease of competing technologies for electricity production
Increased and stable energy production throughout the day due to tracking	Bankability and perception issues due to shorter track record compared to PV
Very low energy payback time	New generation technologies, without a history of production (thus increased risk)
Potential double use of land, e.g. for agriculture. Low environmental impact[1]	Additional optical losses
Opportunities for cost-effective local manufacturing of certain steps	Lack of technology standardization
Less sensitive to variations in semiconductor prices	
Greater potential for efficiency increase in the future compared to single-junction flat plate systems could lead to greater improvements in land area use, system, BOS and BOP costs	

Figure 10. CPV Strengths and Weaknesses. Source: Phillips et al. (2015).

D. COST OF ELECTRICITY

Electricity rates vary nationwide but the national average per kWh has not changed more than a penny per kWh since 2014; see Table 2 (EIA, 2016).

Table 2.   U.S. Average Electricity Price. Adapted from EIA (2016).

	2014	2015	2016
Residential Sector	$.1252	$.1267	$.1261
Commercial Sector	$.1074	$.1059	$.1050
Industrial Sector	$.0710	$.0690	$.0680

Table 2 prices cover the nominal U.S. average price paid per kWh, but prices vary in geographical markets. Of these utility markets, Pacific Gas and Electric's (PG&E) is the largest. In 2014, (the latest data available from EIA) PG&E was the largest utility provider in the U.S. by number of consumers and annual revenue collected (EIA, 2014). In order to achieve such numbers, PG&E covers over 70 thousand square miles of territory and services approximately 16 million customers (PGE, 2016). Such a large, population-dense coverage area poses significant supply and demand related issues for a utility. Due to its size, a wide array of pricing structures, and large coverage in California (a high DNI area), PG&E pricing is used for this study's pricing model.

One way PG&E influences demand is through different combinations of variable rate pricing. Current options for residential customers include tiered base and time of use (TOU) plans. With a tiered plan, customers pay a flat rate for electricity up to a predetermined amount (baseline), then a new higher rate is in effect for use greater than 100%−200% of baseline, and yet another higher rate for any use greater than 200% of baseline (PGE, 2016). Figure 11 illustrates the PG&E tiered pricing plan.
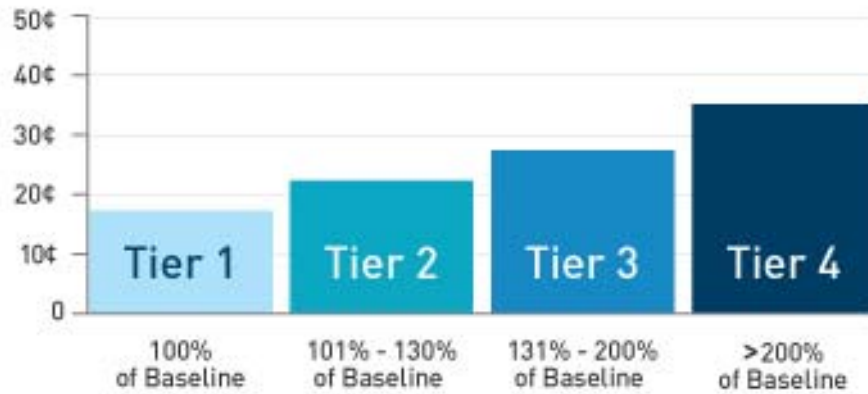
Figure 11. PG&E's Tiered Pricing. Source: PG&E (n.d.b.).

TOU plans vary the price per kWh based on time of day using off-peak, partial-peak, and peak times of demand to set the rate structure. During peak hours (the hours consumer demand is highest in a 24-hour period) the rates are the most expensive (up to $.40/kWh), and rates charged are lower during partial peak and off-peak times. The peak periods are also defined based on seasonal demand patterns such that rates differ from November−April and from May−October, with higher rates during the summer season (PGE, 2016). Figures 12−14 illustrate the peak times and pricing plans for PG&E's 2016 E6 pricing used in this study.
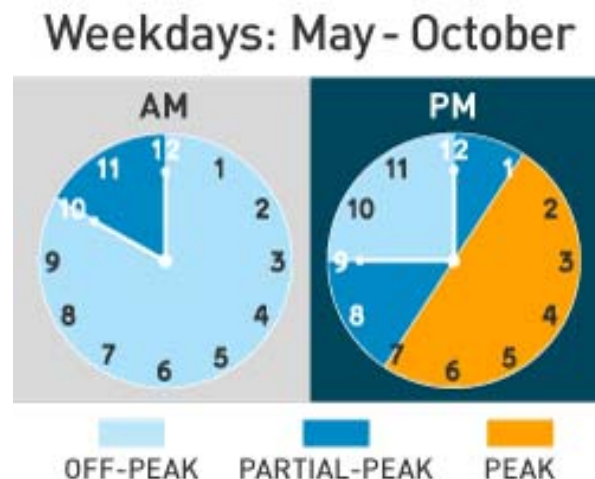
Figure 12.   Peak Times. Source: PG&E (2016).
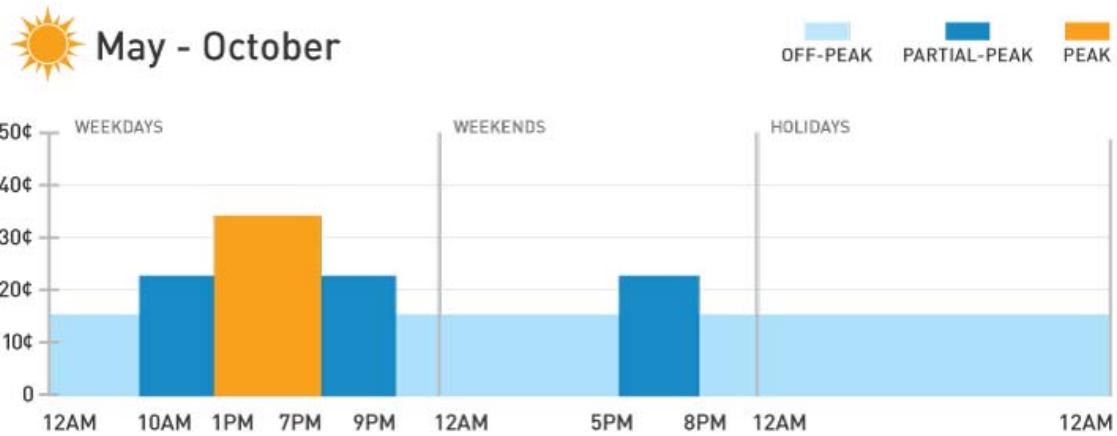
Figure 13.　TOU Summer Rates. Source: PG&E (2016).
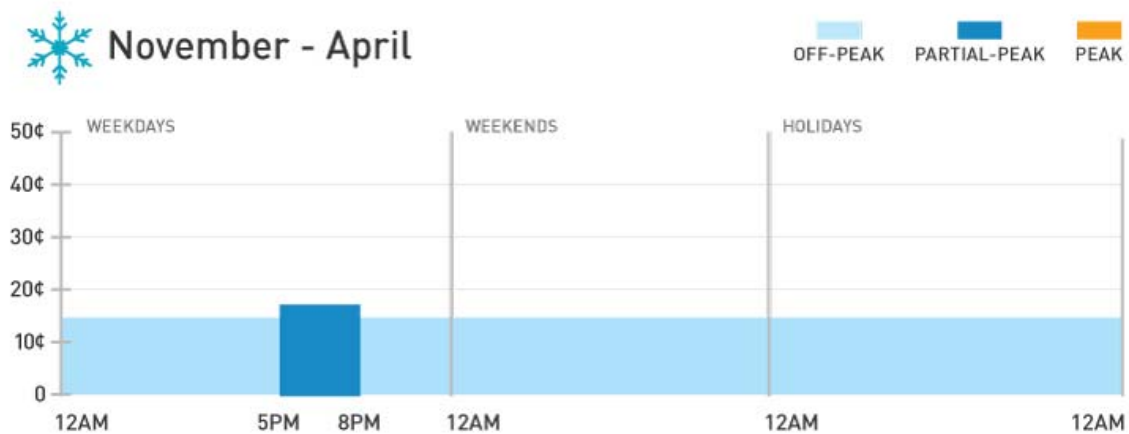
Figure 14.　TOU Winter Rates. Source: PG&E (2016).

The demand influenced pricing of TOU rates favors solar generation. The peak rates and times overlap with late afternoon solar generation. Such overlap adds monetary value to solar produced electricity considering electricity purchased during those periods is more expensive. Thus, electricity produced by solar during peak periods is more valuable or generates more "revenue" for the owner of the system.

III.   METHODOLOGY

In April 2015, NREL created a bottom-up cost model to analyze III-V multi-junction cells and CPV modules. Many components of CPV modules had a two-fold effect on the model, meaning that a change of one component may add significantly to or reduce cost, but also enhance performance of the module. One of the components identified was thermal management or heat sink technology (Horowitz, Woodhouse, Smestad, Lee, Hicks, & Palmer, 2015). A student team at NPS from the Graduate School of Engineering and Applied Science (GSEAS) has been testing different thermal management strategies for CPV applications and has created successful designs for passive cooling. The intent of this study is to analyze the cost impacts of one new heat sink design compared to performance enhancement.

A complete LCOE of a CPV system is necessary to analyze the competitiveness of solar technologies and possibly make predictions of CPV's role in the greater solar market. Assessing one component of a CPV module, benefits from a different approach. Instead of costing each individual component in the work breakdown structure (WBS) of CPV manufacturing and installation, the value of the modules over time was assessed. Simply put, CPV modules generate electricity; electricity has a defined market price for a given location. Therefore, the electricity generated can be measured as a form of revenue for the owner of the system.

Such a top-down view of CPV gives decision makers apples-to-apples comparisons of the value of CPV modules with or without the new heat sink design and an accurate depiction of the system payback period. Net present value (NPV) calculations forecasted for annual cash flows quantify revenue generation for each module. These cash flows represent the ROI over time for multiple combinations of variables

The time required to generate sufficient savings to match the original CAPEX for the system defines the payback period. Operation and support (O&S) costs were not factored in to this analysis, since we assumed the new passive heat sink design would not

add any O&S costs beyond those already incurred under the current design. Therefore, O&S would cancel each other out in comparative analysis.

Careful consideration of both the payback period and the profit beyond payback give decision-makers relevant, measurable data upon which to weigh a CPV purchase decision. A methodology rubric is offered in Figure 15.

Figure 15. Methodology Rubric

IV. DATA ANALYSIS

A. DATA COLLECTION/VARIABLES DEFINED

1. Electricity Rates

Data for analysis was collected from a variety of sources. PG&E TOU rates per kWh were available online and reflect Electric Schedule E6 residential rates from early 2016 (PG&E, 2016). Of note, the E6 pricing plan is set to expire May 10, 2016, when new rates will become available. As a best-case scenario the summer (May–October), weekday, E6 rates were used. Given that the TOU rate fluctuates throughout the day and night, a weighted average was computed to reflect an overall TOU rate of $.32 per kWh.

2. CAPEX

The baseline Capital Expenditure for a CPV module is from a contract cost estimate for an Arzon Solar, uM2 CPV Solar Power Generator. This CAPEX represents the full cost of installing a uM2 generator onsite at Naval Postgraduate School, Monterey. As with any solar installation; costs will vary based on site location, and material and labor required. Using this single module for baseline costs represents somewhat of a worst case scenario as CAPEX per unit is expected to decrease as the quantity of unit ordered increases. Table 3 illustrates the cost estimate from Arzon Solar.

Table 3.   Contracting Cost Estimate for NSAM. Adapted from A. Plesniak, personal communication, March 16, 2016.

Contract Item	Cost Estimate
uM2 Solar Power Generator	$11.8k
PVI-6000 Inverter	$2k
Installation Costs	$5k
Miscellaneous	$2K
TOTAL COST OF INSTALL	**$20.8k**

3.   uM2 Output

uM2 Output in kWh was estimated using the specifications from Arzon Solar's uM2 fact sheet. Concentrator Standard Operating Conditions (CSOC) values were used instead of Concentrator Standard Test Conditions (CSTC) values to more accurately reflect outdoor operating results as opposed to theoretical lab testing. The uM2 Solar Power Generator has a CSOC power rating of 4.6 kW (Arzon, 2016). Using estimated DNI and atmospheric conditions for Monterey the estimated monthly output for a single uM2 generator was calculated to be 795.8 kWh per month.

4.   Monthly Revenue

Revenue was computed by multiplying the values estimated in power output and the weighted average for PG&E TOU rates using the E6 pricing plan. The baseline revenue without adding the new heat sink is $255.29 per month.

$$MonthlyOutput(kWh) \times Rate(\$/kWh) = Revenue(\$/month) \qquad (1)$$

5.   Performance Enhancement

The new heat sink design for passive cooling developed by a GSEAS student has achieved a 1%−3% increase in efficiency over traditional pin fin heat sink designs (Fletcher, 2016). Arzon's uM2 simply uses the aluminum housing of the module to dissipate heat. Pin fin heat sink designs theoretically dissipate heat more effectively in solar generator applications due to, among other things, the additional surface area created in a pin fin design over flat plate (Cheremisinoff, 1986). Therefore, the efficiency gained over pin fin heat sink design correlates to at least a 1%−3% increase in efficiency, if not more. The efficiency increase was applied to the normal monthly output of a uM2 module represented in Equation 2.

$$(\eta(\%) \times MontlyOutput(kWh)) + MonthlyOuput(kWh) = NewHeatSinkMonthlyOutput \ (2)$$

The new heat sink monthly output was then multiplied by the PG&E average TOU rate per kWh to compute a projected monthly revenue generated by the uM2 module.

6.   Discount Rate

A discount rate of 3% was used in compliance with OMB Circular No. A-94, Appendix C; reference lease-purchase and cost-effectiveness analysis (Donovan, 2016).

7.   Time Period

Time period for return on investment (ROI) evaluation was set to 25 years. Using the national residential flat rate projection of $.1261 per kWh (Table 2) as a low end assessment, the payback period for the baseline CAPEX ($20,800) was 25 years. As previously mentioned, solar generators are more financially attractive in areas that have TOU rate pricing and can take advantage of higher electricity rates. Thus, the remainder of quantitative analysis uses the weighted average of TOU rate to compute monthly revenue and determine payback periods.

B.   VARIABLES DEFINED

Beyond data collection, the primary variables adjusted for sensitivity analysis were CAPEX and monthly revenue. The baseline values of a $20,800.00 CAPEX and monthly revenue of $255.29 per month were adjusted incrementally by percentage. Industry data was unavailable for the actual cost of manufacturing and installing the new heat sink design as the design is a prototype and not currently being manufactured. NREL's 2015, *A Bottom-up Cost Analysis of a High Concentration PV Module,* estimated thermal management costs made up 5.4% of total CPV costs (Horowitz, 2015). Using NREL's findings, the new heat sink design costs were analyzed from 1%−7% of the baseline $20,800 CAPEX.

Monthly revenue sensitivity reflects the range of performance improvement possible using the new heat sink design. Monthly output was adjusted by increasing output from 1%−3%, and computing the new respective revenue for each enhancement.

All other components of data collection were held constant as CAPEX and monthly revenue inputs were varied for analysis.

C.   DISCOUNTED CASH FLOWS

The baseline scenario for determining initial payback period and total ROI was as follows in Table 4.

Table 4.   Baseline Scenario

One uM2	
r (annual)	0.03
Intial cost	(20,800.00)
Monthly CF	255.29
Yearly CF	3,063.48

Monthly cash flow was multiplied by 12 to compute yearly cash flow, and the yearly cash flow was then discounted on an annual basis from year 25 to present day or year zero, using Equation 3.

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)} \tag{3}$$

The 25 years of cash flows were summed with and without the initial CAPEX for comparison and to facilitate ROI comparison calculations. As an example, Table 5 depicts the cash flow computations for the baseline scenario.

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Table 5.   Baseline Cash Flow Scenario

Year	Cash Flow	ROI
0	(20,800.00)	
1	2,974.25	(17,825.75)
2	2,887.62	(14,938.12)
3	2,803.52	(12,134.61)
4	2,721.86	(9,412.74)
5	2,642.58	(6,770.16)
6	2,565.62	(4,204.54)
7	2,490.89	(1,713.65)
8	2,418.34	704.69
9	2,347.90	3,052.59
10	2,279.52	5,332.11
11	2,213.12	7,545.23
12	2,148.66	9,693.89
13	2,086.08	11,779.97
14	2,025.32	13,805.29
15	1,966.33	15,771.63
16	1,909.06	17,680.68
17	1,853.46	19,534.14
18	1,799.47	21,333.61
19	1,747.06	23,080.67
20	1,696.17	24,776.85
21	1,646.77	26,423.62
22	1,598.81	28,022.43
23	1,552.24	29,574.67
24	1,507.03	31,081.69
25	1,463.14	32,544.83
No CAPEX Sum	53,344.83	
Sum w/ CAPEX	32,544.83	

In Table 5, the No CAPEX sum represents the sum of all discounted cash flows except year zero; the sum with CAPEX includes the year zero expenditure of $20,800. Thus, the sum with CAPEX, denotes the net present value (NPV) of a uM2 system kept for 25 years to be $32,544.83

D. SENSITIVITY ANALYSIS

The Table 5 computations were repeated holding all else constant except for the variables of CAPEX and monthly cash flows (see Table 4) or revenue. All combinations of varying additional CAPEX costs from 1%−7% and additional monthly revenues from 1%–3% were computed, thereby creating 21 sensitivity analysis tables shown in the Appendix. The sensitivity analysis tables compute the change as compared to the baseline computations in Table 5 rather than the total amount for each scenario. An example of the sensitivity tables is depicted in Table 6, in which CAPEX is increased by 1% above its base value and efficiency is increased by 1%, 2%, and 3% above its base value.

Table 6.   CAPEX +1%, Efficiency 1%−3% Sensitivity Tables

Cost	Eff			Cost	Eff			Cost	Eff		
0.01	0.01			0.01	0.02			0.01	0.03		
r (annual)	0.03			r (annual)	0.03			r (annual)	0.03		
Capex Δ	(208.00)			Capex Δ	(208.00)			Capex Δ	(208.00)		
Monthly CF	257.84	Monthly CF Δ	2.55	Monthly CF	260.40	Monthly CF Δ	5.11	Monthly CF	262.95	Monthly CF Δ	7.66
Yearly CF	3,094.11	Yearly CF Δ	30.63	Yearly CF	3,124.75	Yearly CF Δ	61.27	Yearly CF	3,155.38	Yearly CF Δ	91.90
	(208.00)				(208.00)				(208.00)		
	29.74	(178.26)			59.49	(148.51)			89.23	(118.77)	
	28.88	(149.38)			57.75	(90.76)			86.63	(32.14)	
	28.04	(121.35)			56.07	(34.69)			84.11	51.96	
	27.22	(94.13)			54.44	19.75			81.66	133.62	
	26.43	(67.70)			52.85	72.60			79.28	212.90	
	25.66	(42.05)			51.31	123.91			76.97	289.86	
	24.91	(17.14)			49.82	173.73			74.73	364.59	
	24.18	7.05			48.37	222.09			72.55	437.14	
	23.48	30.53			46.96	269.05			70.44	507.58	
	22.80	53.32			45.59	314.64			68.39	575.96	
	22.13	75.45			44.26	358.90			66.39	642.36	
	21.49	96.94			42.97	401.88			64.46	706.82	
	20.86	117.80			41.72	443.60			62.58	769.40	
	20.25	138.05			40.51	484.11			60.76	830.16	
	19.66	157.72			39.33	523.43			58.99	889.15	
	19.09	176.81			38.18	561.61			57.27	946.42	
	18.53	195.34			37.07	598.68			55.60	1,002.02	
	17.99	213.34			35.99	634.67			53.98	1,056.01	
	17.47	230.81			34.94	669.61			52.41	1,108.42	
	16.96	247.77			33.92	703.54			50.89	1,159.31	
	16.47	264.24			32.94	736.47			49.40	1,208.71	
	15.99	280.22			31.98	768.45			47.96	1,256.67	
	15.52	295.75			31.04	799.49			46.57	1,303.24	
	15.07	310.82			30.14	829.63			45.21	1,348.45	
	14.63	325.45			29.26	858.90			43.89	1,392.34	
No CAPEX Sum	533.45			No CAPEX Sum	1,066.90			No CAPEX Sum	1,600.34		
Sum w/ CAPEX	325.45	3.8392% ROI		Sum w/ CAPEX	858.90	6.7585% ROI		Sum w/ CAPEX	1,392.34	8.5041% ROI	

For all three Table 6 scenarios, a 1% increase in cost or CAPEX is depicted and a performance increase of 1%−3% improves monthly revenue totals. For example, a cost increase of 1% equates to a $208.00 increase in cost over the initial $20,800 CAPEX and the 1% increase in efficiency increases monthly revenue by $2.55 (Table 6). The new monthly revenue drives the yearly cash flow and this cash flow is discounted for 25 yrs.

The %ROI is computed by Equation 4, NoCAPEXSUM is defined in Table 5, delta CAPEX is the increase or change to the baseline CAPEX of $20,800.

$$\sqrt[25]{\frac{NoCAPEXSUM}{\Delta CAPEX}} - 1 \qquad (4)$$

The %ROI value describes the ROI attributed to all changes from the baseline scenario from Table 5. A range of ROI values can then computed for the full range of possible CAPEX increases. Figure 16 depicts this relationship for a 1% increase in performance.
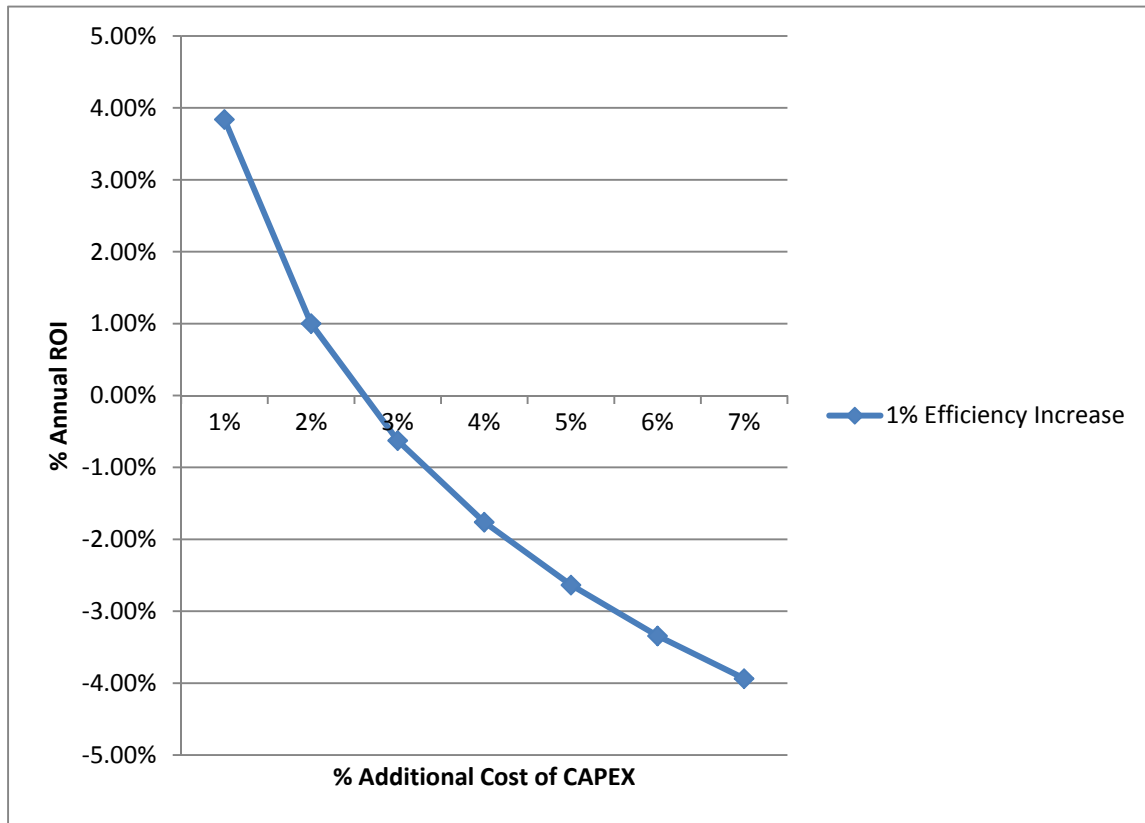
Figure 16. ROI vs. CAPEX with 1% Efficiency Increase

Of note, beyond approximately a 2.5% increase in CAPEX the ROI becomes negative for a 1% increase in generator performance.

Figure 17, depicts the same relationship for all three performance possibilities, namely efficiency increases of 1%, 2%, and 3%.
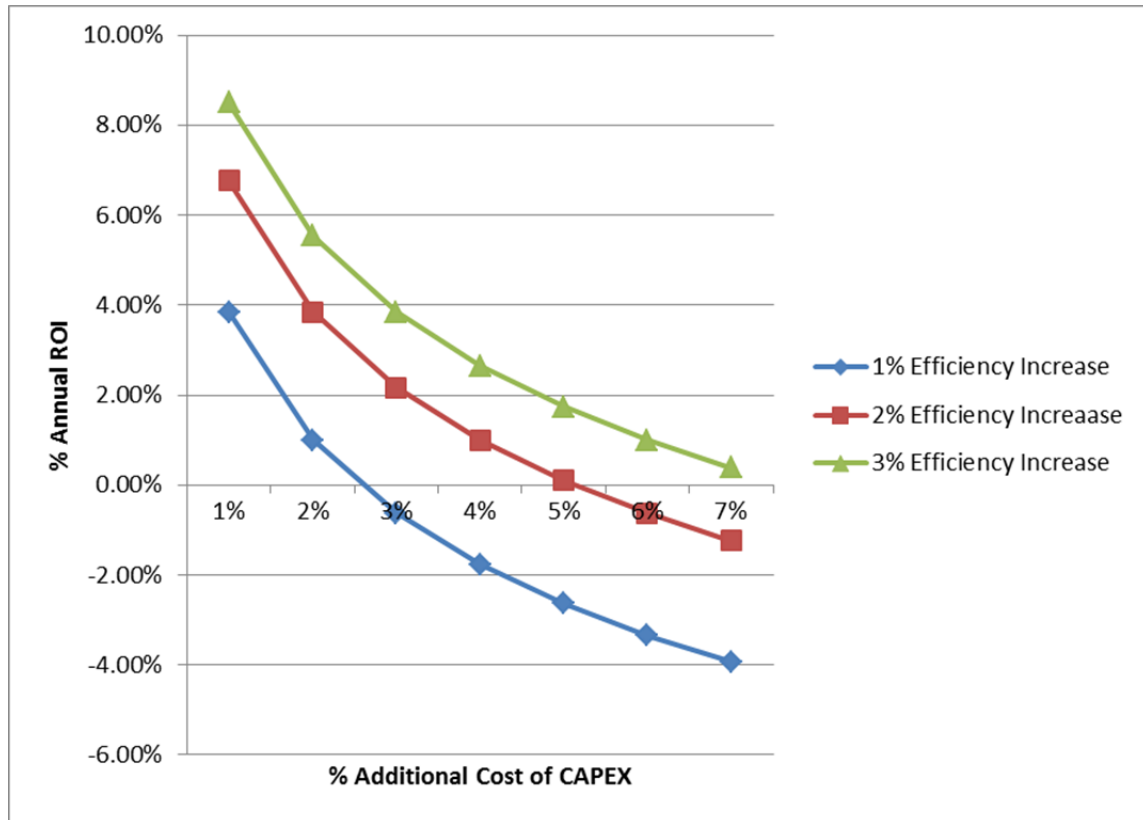
Figure 17. ROI vs. CAPEX

As expected, Overall ROI performance increases as efficiency increases. Notably, a 3% efficiency increase keeps ROI positive throughout all CAPEX variations. Considering NREL's estimation of heat sinks making up 5.4% of CAPEX, the 5% additional cost of CAPEX is a relevant data point to consider (Horowitz, 2015). At 5% additional cost of CAPEX, only 2% and 3% increases in efficiency generate a positive %ROI. Also, at 5% or greater additional cost, the %ROI is less than 2% for all efficiencies.

Beyond initial scenario ROI vs. CAPEX relationships, a useful tool is to predict what levels of efficiencies are required to reach a predetermined ROI. We chose 5% and 8% as notional ROI thresholds in order to demonstrate this approach. Figures 18–20

depict increased levels of efficiency or better performance with both 5% and 8% reference thresholds for ROI.
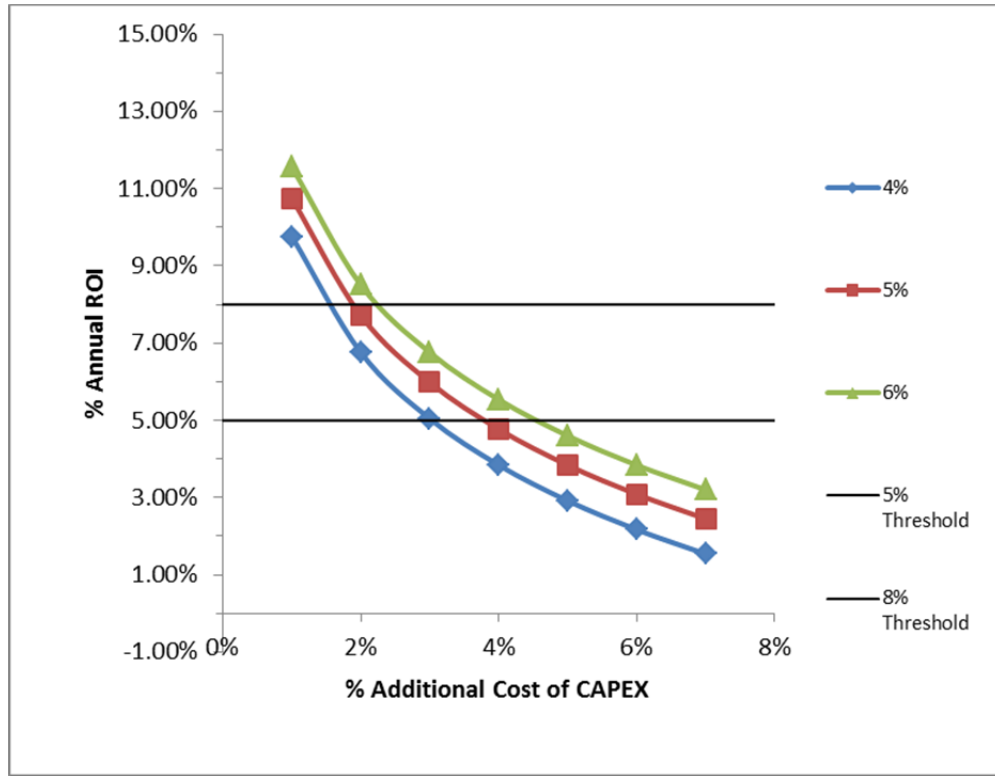
Figure 18. ROI vs. CAPEX 4%−6% Efficiency
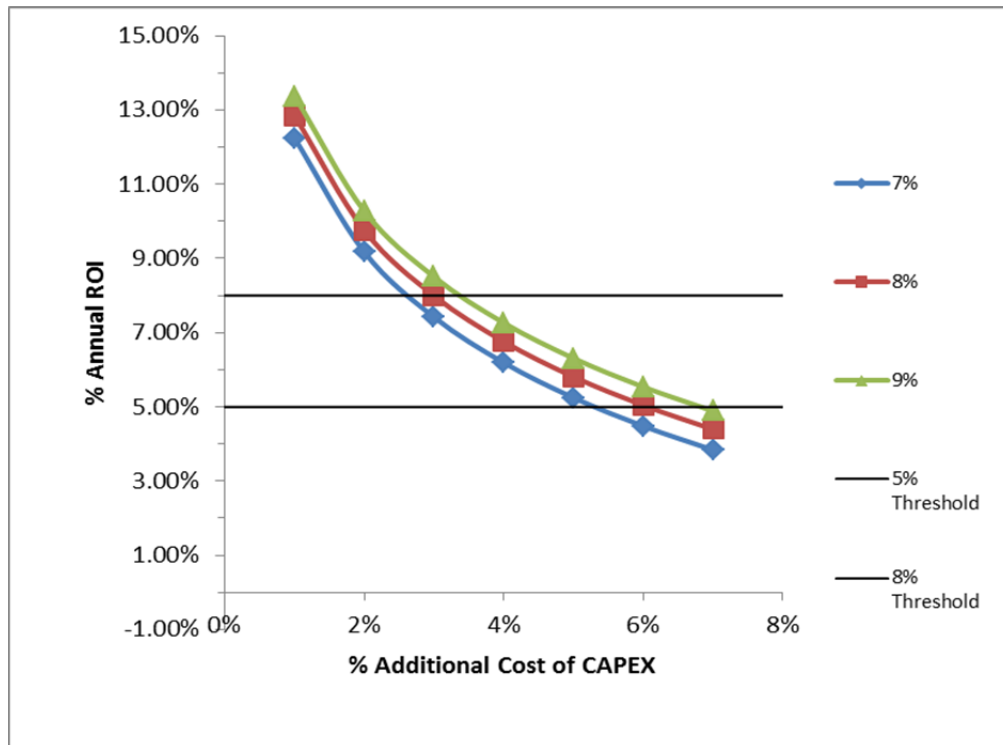
Figure 19. ROI vs. CAPEX 7%−9% Efficiency
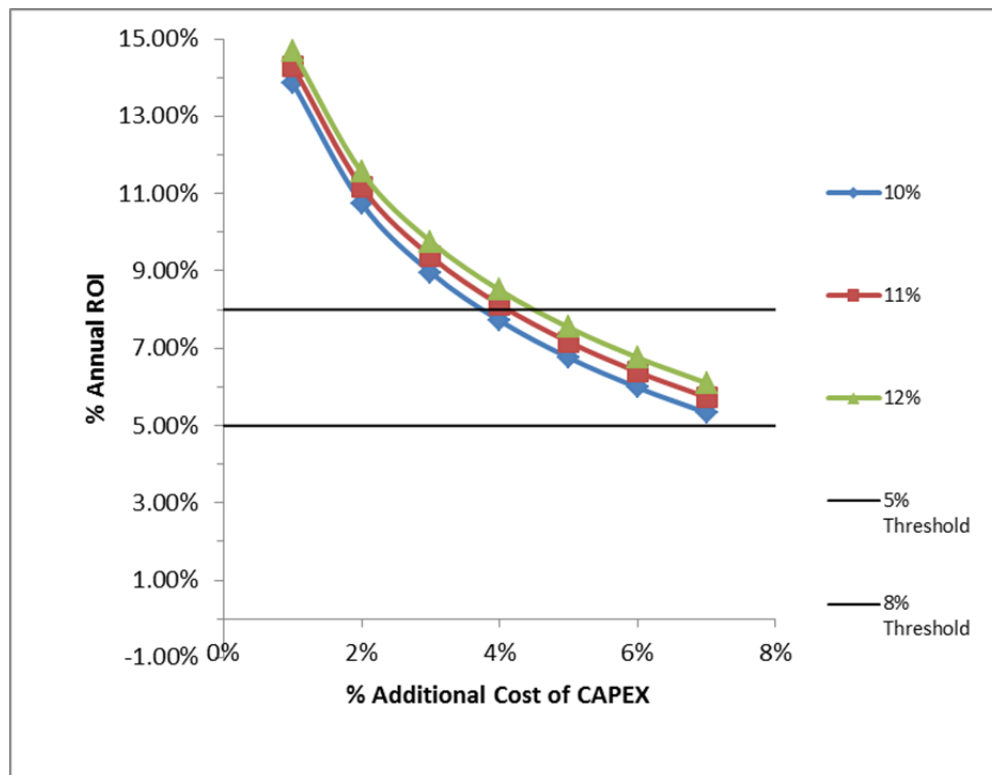
Figure 20. ROI vs. CAPEX 10%−12% Efficiency

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Of the three efficiency ranges in Figures 18–20, only an efficiency increase of 10% or greater (Figure 20) remains above the 5% ROI threshold for all CAPEX increases from 1%−7%. Only 11% or greater efficiencies remain above the 8% ROI threshold when costs are 4% or less. The 5% additional cost of CAPEX data point becomes significant with regard to %ROI thresholds. Efficiency increases of 6% and below do not meet or exceed the 5% ROI threshold, as is seen in Figure 19. However, efficiency increases of 7% and above remain above the 5% ROI threshold at 5% additional cost of CAPEX, as seen in Figures 19 and 20.

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V. CONCLUSION

This thesis formulates a credible, reasonable, and professionally developed cost analysis of adding a new heat sink design to an existing CPV system. Broad research was conducted to better understand the key fundamentals behind solar power generation and more specifically CPV systems. Additionally, insight into the solar generation market was also researched through analyzing electricity rate data, CPV market research, and a firsthand account with an industry representative from a commercial solar generator company.

Three primary cost drivers were researched and analyzed. First, actual data from a commercial manufacturer (Arzon) of CPV systems was used to estimate purchase and installation costs of an Arzon uM2 solar power generator at the Naval Postgraduate School. Second, electricity rates for the local area were used to calculate a reasonable estimate of how much revenue a uM2 solar power generator could produce over time. Third, as the new heat sink design developed at NPS has not been manufactured beyond the prototype phase, production costs for the new heat were predicted as a portion of initial CAPEX based on a previous bottom–up costing model (Horowitz et al., 2015). Sensitivity analysis was conducted varying the efficiencies gained from use of the new heat sink design versus relative cost impacts.

Notable relationships from the sensitivity analyses are as follows:

a. ***%ROI increases as efficiency increases.***

b. ***%ROI decreases as additional cost of CAPEX increases.***

c. ***Using 5% additional cost of CAPEX as a reasonable benchmark:***

   (1) 2% or greater efficiency is required to keep %ROI greater than zero, a minimum for even considering making this investment.

   (2) 7% or greater efficiency is required to exceed a 5%ROI threshold, a first threshold at which we should consider making this investment.

The specific heat sink design as tested may or may not fit specific ROI requirements desired for future projects. Thus, the 5% and 8% ROI thresholds become useful to predict what efficiencies are necessary as a function of additional cost to meet or exceed ROI desired. This work gives future researchers efficiency and cost targets to reference for predicting whether or not adding a new heat sink is a sound business decision.

The decision space offered by our research provides %ROI feedback over a 25 year lifespan for a specific CPV project in Monterey, CA. The model used can be scaled up for larger projects in different locations by accurately adjusting the CAPEX and monthly revenue variables. For instance, a larger scale project is likely to reduce CAPEX per unit due to relative economies of scale advantages for commercial producers. Additionally, the electricity rates for the area will greatly impact the monthly revenue and produced by each unit.

Areas for future research:

- Investigate cost comparisons of commercially available PV vs. CPV solar generators for specific DOD installations.

- Research large-scale cost data for CPV solar generators to identify advantageous quantities for desired ROI predictions.

- Research modern heat design manufacturing methods and relative cost.

- Investigate the viability of heat sinks being added to off the shelf CPV solar generators versus incorporation in original manufacturing of a CPV module.

- Collect data points from an actual CPV solar generator with and without heat sinks to measure efficiency increases.

- Collect sample data comparing efficiencies of modern heat sink design versus flat plate heat sink.

APPENDIX. SENSITIVITY ANALYSIS TABLES FOR CAPEX AND REVENUE VARIATIONS

Table 1

Cost	Eff	
0.01	0.01	
r (annual)	0.03	
Capex Δ	(208.00)	
Monthly CF	257.84 Monthly CF Δ	2.55
Yearly CF	3,094.11 Yearly CF Δ	30.63

(208.00)	
29.74	(178.26)
28.88	(149.38)
28.04	(121.35)
27.22	(94.13)
26.43	(67.70)
25.66	(42.05)
24.91	(17.14)
24.18	7.05
23.48	30.53
22.80	53.32
22.13	75.45
21.49	96.94
20.86	117.80
20.25	138.05
19.66	157.72
19.09	176.81
18.53	195.34
17.99	213.34
17.47	230.81
16.96	247.77
16.47	264.24
15.99	280.22
15.52	295.75
15.07	310.82
14.63	325.45
No CAPEX Sum	533.45
Sum w/ CAPEX	325.45 — 3.8392% ROI

Table 2

Cost	Eff	
0.01	0.02	
r (annual)	0.03	
Capex Δ	(208.00)	
Monthly CF	260.40 Monthly CF Δ	5.11
Yearly CF	3,124.75 Yearly CF Δ	61.27

(208.00)	
59.49	(148.51)
57.75	(90.76)
56.07	(34.69)
54.44	19.75
52.85	72.60
51.31	123.91
49.82	173.73
48.37	222.09
46.96	269.05
45.59	314.64
44.26	358.90
42.97	401.88
41.72	443.60
40.51	484.11
39.33	523.43
38.18	561.61
37.07	598.68
35.99	634.67
34.94	669.61
33.92	703.54
32.94	736.47
31.98	768.45
31.04	799.49
30.14	829.63
29.26	858.90
No CAPEX Sum	1,066.90
Sum w/ CAPEX	858.90 — 6.7585% ROI

Table 3

Cost	Eff	
0.01	0.03	
r (annual)	0.03	
Capex Δ	(208.00)	
Monthly CF	262.95 Monthly CF Δ	7.66
Yearly CF	3,155.38 Yearly CF Δ	91.90

(208.00)	
89.23	(118.77)
86.63	(32.14)
84.11	51.96
81.66	133.62
79.28	212.90
76.97	289.86
74.73	364.59
72.55	437.14
70.44	507.58
68.39	575.96
66.39	642.36
64.46	706.82
62.58	769.40
60.76	830.16
58.99	889.15
57.27	946.42
55.60	1,002.02
53.98	1,056.01
52.41	1,108.42
50.89	1,159.31
49.40	1,208.71
47.96	1,256.67
46.57	1,303.24
45.21	1,348.45
43.89	1,392.34
No CAPEX Sum	1,600.34
Sum w/ CAPEX	1,392.34 — 8.5041% ROI

Table 4

Cost	Eff		
0.02	0.01		
r (annual)	0.03		
Capex Δ	(416.00)		
Monthly CF	257.84 Monthly CF Δ	2.55	
Yearly CF	3,094.11 Yearly CF Δ	30.63	

0	(416.00)	
1	29.74	(386.26)
2	28.88	(357.38)
3	28.04	(329.35)
4	27.22	(302.13)
5	26.43	(275.70)
6	25.66	(250.05)
7	24.91	(225.14)
8	24.18	(200.95)
9	23.48	(177.47)
10	22.80	(154.68)
11	22.13	(132.55)
12	21.49	(111.06)
13	20.86	(90.20)
14	20.25	(69.95)
15	19.66	(50.28)
16	19.09	(31.19)
17	18.53	(12.66)
18	17.99	5.34
19	17.47	22.81
20	16.96	39.77
21	16.47	56.24
22	15.99	72.22
23	15.52	87.75
24	15.07	102.82
25	14.63	117.45
No CAPEX Sum	533.45	
Sum w/ CAPEX	117.45	0.9997% ROI

Table 5

Cost	Eff		
0.02	0.02		
r (annual)	0.03		
Capex Δ	(416.00)		
Monthly CF	260.40 Monthly CF Δ	5.11	
Yearly CF	3,124.75 Yearly CF Δ	61.27	

0	(416.00)	
1	59.49	(356.51)
2	57.75	(298.76)
3	56.07	(242.69)
4	54.44	(188.25)
5	52.85	(135.40)
6	51.31	(84.09)
7	49.82	(34.27)
8	48.37	14.09
9	46.96	61.05
10	45.59	106.64
11	44.26	150.90
12	42.97	193.88
13	41.72	235.60
14	40.51	276.11
15	39.33	315.43
16	38.18	353.61
17	37.07	390.68
18	35.99	426.67
19	34.94	461.61
20	33.92	495.54
21	32.94	528.47
22	31.98	560.45
23	31.04	591.49
24	30.14	621.63
25	29.26	650.90
No CAPEX Sum	1,066.90	
Sum w/ CAPEX	650.90	3.8392% ROI

Table 6

Cost	Eff		
0.02	0.03		
r (annual)	0.03		
Capex Δ	(416.00)		
Monthly CF	262.95 Monthly CF Δ	7.66	
Yearly CF	3,155.38 Yearly CF Δ	91.90	

0	(416.00)	
1	89.23	(326.77)
2	86.63	(240.14)
3	84.11	(156.04)
4	81.66	(74.38)
5	79.28	4.90
6	76.97	81.86
7	74.73	156.59
8	72.55	229.14
9	70.44	299.58
10	68.39	367.96
11	66.39	434.36
12	64.46	498.82
13	62.58	561.40
14	60.76	622.16
15	58.99	681.15
16	57.27	738.42
17	55.60	794.02
18	53.98	848.01
19	52.41	900.42
20	50.89	951.31
21	49.40	1,000.71
22	47.96	1,048.67
23	46.57	1,095.24
24	45.21	1,140.45
25	43.89	1,184.34
No CAPEX Sum	1,600.34	
Sum w/ CAPEX	1,184.34	5.5370% ROI

Cost 0.03 / Eff 0.01

Cost	Eff	
0.03	0.01	
r (annual)	0.03	
Capex Δ	(624.00)	
Monthly CF	257.84	Monthly CF Δ 2.55
Yearly CF	3,094.11	Yearly CF Δ 30.63
0	(624.00)	
1	29.74	(594.26)
2	28.88	(565.38)
3	28.04	(537.35)
4	27.22	(510.13)
5	26.43	(483.70)
6	25.66	(458.05)
7	24.91	(433.14)
8	24.18	(408.95)
9	23.48	(385.47)
10	22.80	(362.68)
11	22.13	(340.55)
12	21.49	(319.06)
13	20.86	(298.20)
14	20.25	(277.95)
15	19.66	(258.28)
16	19.09	(239.19)
17	18.53	(220.66)
18	17.99	(202.66)
19	17.47	(185.19)
20	16.96	(168.23)
21	16.47	(151.76)
22	15.99	(135.78)
23	15.52	(120.25)
24	15.07	(105.18)
25	14.63	(90.55)
No CAPEX Sum	533.45	
Sum w/ CAPEX	(90.55)	-0.6252% ROI

Cost 0.03 / Eff 0.02

Cost	Eff	
0.03	0.02	
r (annual)	0.03	
Capex Δ	(624.00)	
Monthly CF	260.40	Monthly CF Δ 5.11
Yearly CF	3,124.75	Yearly CF Δ 61.27
0	(624.00)	
1	59.49	(564.51)
2	57.75	(506.76)
3	56.07	(450.69)
4	54.44	(396.25)
5	52.85	(343.40)
6	51.31	(292.09)
7	49.82	(242.27)
8	48.37	(193.91)
9	46.96	(146.95)
10	45.59	(101.36)
11	44.26	(57.10)
12	42.97	(14.12)
13	41.72	27.60
14	40.51	68.11
15	39.33	107.43
16	38.18	145.61
17	37.07	182.68
18	35.99	218.67
19	34.94	253.61
20	33.92	287.54
21	32.94	320.47
22	31.98	352.45
23	31.04	383.49
24	30.14	413.63
25	29.26	442.90
No CAPEX Sum	1,066.90	
Sum w/ CAPEX	442.90	2.1686% ROI

Cost 0.03 / Eff 0.03

Cost	Eff	
0.03	0.03	
r (annual)	0.03	
Capex Δ	(624.00)	
Monthly CF	262.95	Monthly CF Δ 7.66
Yearly CF	3,155.38	Yearly CF Δ 91.90
0	(624.00)	
1	89.23	(534.77)
2	86.63	(448.14)
3	84.11	(364.04)
4	81.66	(282.38)
5	79.28	(203.10)
6	76.97	(126.14)
7	74.73	(51.41)
8	72.55	21.14
9	70.44	91.58
10	68.39	159.96
11	66.39	226.36
12	64.46	290.82
13	62.58	353.40
14	60.76	414.16
15	58.99	473.15
16	57.27	530.42
17	55.60	586.02
18	53.98	640.01
19	52.41	692.42
20	50.89	743.31
21	49.40	792.71
22	47.96	840.67
23	46.57	887.24
24	45.21	932.45
25	43.89	976.34
No CAPEX Sum	1,600.34	
Sum w/ CAPEX	976.34	3.8392% ROI

Cost 0.04 / Eff 0.01

Cost	Eff	
0.04	0.01	
r (annual)	0.03	
Capex Δ	(832.00)	
Monthly CF	257.84	Monthly CF Δ 2.55
Yearly CF	3,094.11	Yearly CF Δ 30.63
0	(832.00)	
1	29.74	(802.26)
2	28.88	(773.38)
3	28.04	(745.35)
4	27.22	(718.13)
5	26.43	(691.70)
6	25.66	(666.05)
7	24.91	(641.14)
8	24.18	(616.95)
9	23.48	(593.47)
10	22.80	(570.68)
11	22.13	(548.55)
12	21.49	(527.06)
13	20.86	(506.20)
14	20.25	(485.95)
15	19.66	(466.28)
16	19.09	(447.19)
17	18.53	(428.66)
18	17.99	(410.66)
19	17.47	(393.19)
20	16.96	(376.23)
21	16.47	(359.76)
22	15.99	(343.78)
23	15.52	(328.25)
24	15.07	(313.18)
25	14.63	(298.55)
No CAPEX Sum	533.45	
Sum w/ CAPEX	(298.55)	-1.7622% ROI

Cost 0.04 / Eff 0.02

Cost	Eff	
0.04	0.02	
r (annual)	0.03	
Capex Δ	(832.00)	
Monthly CF	260.40	Monthly CF Δ 5.11
Yearly CF	3,124.75	Yearly CF Δ 61.27
0	(832.00)	
1	59.49	(772.51)
2	57.75	(714.76)
3	56.07	(658.69)
4	54.44	(604.25)
5	52.85	(551.40)
6	51.31	(500.09)
7	49.82	(450.27)
8	48.37	(401.91)
9	46.96	(354.95)
10	45.59	(309.36)
11	44.26	(265.10)
12	42.97	(222.12)
13	41.72	(180.40)
14	40.51	(139.89)
15	39.33	(100.57)
16	38.18	(62.39)
17	37.07	(25.32)
18	35.99	10.67
19	34.94	45.61
20	33.92	79.54
21	32.94	112.47
22	31.98	144.45
23	31.04	175.49
24	30.14	205.63
25	29.26	234.90
No CAPEX Sum	1,066.90	
Sum w/ CAPEX	234.90	0.9997% ROI

Cost 0.04 / Eff 0.03

Cost	Eff	
0.04	0.03	
r (annual)	0.03	
Capex Δ	(832.00)	
Monthly CF	262.95	Monthly CF Δ 7.66
Yearly CF	3,155.38	Yearly CF Δ 91.90
0	(832.00)	
1	89.23	(742.77)
2	86.63	(656.14)
3	84.11	(572.04)
4	81.66	(490.38)
5	79.28	(411.10)
6	76.97	(334.14)
7	74.73	(259.41)
8	72.55	(186.86)
9	70.44	(116.42)
10	68.39	(48.04)
11	66.39	18.36
12	64.46	82.82
13	62.58	145.40
14	60.76	206.16
15	58.99	265.15
16	57.27	322.42
17	55.60	378.02
18	53.98	432.01
19	52.41	484.42
20	50.89	535.31
21	49.40	584.71
22	47.96	632.67
23	46.57	679.24
24	45.21	724.45
25	43.89	768.34
No CAPEX Sum	1,600.34	
Sum w/ CAPEX	768.34	2.6511% ROI

Table 1

Cost	Eff		
0.05	0.01		
r (annual)	0.03		
Capex Δ	(1,040.00)		
Monthly CF	257.84	Monthly CF Δ	2.55
Yearly CF	3,094.11	Yearly CF Δ	30.63

0	(1,040.00)	
1	29.74	(1,010.26)
2	28.88	(981.38)
3	28.04	(953.35)
4	27.22	(926.13)
5	26.43	(899.70)
6	25.66	(874.05)
7	24.91	(849.14)
8	24.18	(824.95)
9	23.48	(801.47)
10	22.80	(778.68)
11	22.13	(756.55)
12	21.49	(735.06)
13	20.86	(714.20)
14	20.25	(693.95)
15	19.66	(674.28)
16	19.09	(655.19)
17	18.53	(636.66)
18	17.99	(618.66)
19	17.47	(601.19)
20	16.96	(584.23)
21	16.47	(567.76)
22	15.99	(551.78)
23	15.52	(536.25)
24	15.07	(521.18)
25	14.63	(506.55)
No CAPEX Sum	533.45	
Sum w/ CAPEX	(506.55)	-2.6351% ROI

Table 2

Cost	Eff		
0.05	0.02		
r (annual)	0.03		
Capex Δ	(1,040.00)		
Monthly CF	260.40	Monthly CF Δ	5.11
Yearly CF	3,124.75	Yearly CF Δ	61.27

0	(1,040.00)	
1	59.49	(980.51)
2	57.75	(922.76)
3	56.07	(866.69)
4	54.44	(812.25)
5	52.85	(759.40)
6	51.31	(708.09)
7	49.82	(658.27)
8	48.37	(609.91)
9	46.96	(562.95)
10	45.59	(517.36)
11	44.26	(473.10)
12	42.97	(430.12)
13	41.72	(388.40)
14	40.51	(347.89)
15	39.33	(308.57)
16	38.18	(270.39)
17	37.07	(233.32)
18	35.99	(197.33)
19	34.94	(162.39)
20	33.92	(128.46)
21	32.94	(95.53)
22	31.98	(63.55)
23	31.04	(32.51)
24	30.14	(2.37)
25	29.26	26.90
No CAPEX Sum	1,066.90	
Sum w/ CAPEX	26.90	0.1022% ROI

Table 3

Cost	Eff		
0.05	0.03		
r (annual)	0.03		
Capex Δ	(1,040.00)		
Monthly CF	262.95	Monthly CF Δ	7.66
Yearly CF	3,155.38	Yearly CF Δ	91.90

0	(1,040.00)	
1	89.23	(950.77)
2	86.63	(864.14)
3	84.11	(780.04)
4	81.66	(698.38)
5	79.28	(619.10)
6	76.97	(542.14)
7	74.73	(467.41)
8	72.55	(394.86)
9	70.44	(324.42)
10	68.39	(256.04)
11	66.39	(189.64)
12	64.46	(125.18)
13	62.58	(62.60)
14	60.76	(1.84)
15	58.99	57.15
16	57.27	114.42
17	55.60	170.02
18	53.98	224.01
19	52.41	276.42
20	50.89	327.31
21	49.40	376.71
22	47.96	424.67
23	46.57	471.24
24	45.21	516.45
25	43.89	560.34
No CAPEX Sum	1,600.34	
Sum w/ CAPEX	560.34	1.7389% ROI

Table 4

Cost	Eff		
0.06	0.01		
r (annual)	0.03		
Capex Δ	(1,248.00)		
Monthly CF	257.84	Monthly CF Δ	2.55
Yearly CF	3,094.11	Yearly CF Δ	30.63

0	(1,248.00)	
1	29.74	(1,218.26)
2	28.88	(1,189.38)
3	28.04	(1,161.35)
4	27.22	(1,134.13)
5	26.43	(1,107.70)
6	25.66	(1,082.05)
7	24.91	(1,057.14)
8	24.18	(1,032.95)
9	23.48	(1,009.47)
10	22.80	(986.68)
11	22.13	(964.55)
12	21.49	(943.06)
13	20.86	(922.20)
14	20.25	(901.95)
15	19.66	(882.28)
16	19.09	(863.19)
17	18.53	(844.66)
18	17.99	(826.66)
19	17.47	(809.19)
20	16.96	(792.23)
21	16.47	(775.76)
22	15.99	(759.78)
23	15.52	(744.25)
24	15.07	(729.18)
25	14.63	(714.55)
No CAPEX Sum	533.45	
Sum w/ CAPEX	(714.55)	-3.3426% ROI

Table 5

Cost	Eff		
0.06	0.02		
r (annual)	0.03		
Capex Δ	(1,248.00)		
Monthly CF	260.40	Monthly CF Δ	5.11
Yearly CF	3,124.75	Yearly CF Δ	61.27

0	(1,248.00)	
1	59.49	(1,188.51)
2	57.75	(1,130.76)
3	56.07	(1,074.69)
4	54.44	(1,020.25)
5	52.85	(967.40)
6	51.31	(916.09)
7	49.82	(866.27)
8	48.37	(817.91)
9	46.96	(770.95)
10	45.59	(725.36)
11	44.26	(681.10)
12	42.97	(638.12)
13	41.72	(596.40)
14	40.51	(555.89)
15	39.33	(516.57)
16	38.18	(478.39)
17	37.07	(441.32)
18	35.99	(405.33)
19	34.94	(370.39)
20	33.92	(336.46)
21	32.94	(303.53)
22	31.98	(271.55)
23	31.04	(240.51)
24	30.14	(210.37)
25	29.26	(181.10)
No CAPEX Sum	1,066.90	
Sum w/ CAPEX	(181.10)	-0.6252% ROI

Table 6

Cost	Eff		
0.06	0.03		
r (annual)	0.03		
Capex Δ	(1,248.00)		
Monthly CF	262.95	Monthly CF Δ	7.66
Yearly CF	3,155.38	Yearly CF Δ	91.90

0	(1,248.00)	
1	89.23	(1,158.77)
2	86.63	(1,072.14)
3	84.11	(988.04)
4	81.66	(906.38)
5	79.28	(827.10)
6	76.97	(750.14)
7	74.73	(675.41)
8	72.55	(602.86)
9	70.44	(532.42)
10	68.39	(464.04)
11	66.39	(397.64)
12	64.46	(333.18)
13	62.58	(270.60)
14	60.76	(209.84)
15	58.99	(150.85)
16	57.27	(93.58)
17	55.60	(37.98)
18	53.98	16.01
19	52.41	68.42
20	50.89	119.31
21	49.40	168.71
22	47.96	216.67
23	46.57	263.24
24	45.21	308.45
25	43.89	352.34
No CAPEX Sum	1,600.34	
Sum w/ CAPEX	352.34	0.9997% ROI

Panel 1

	Cost	Eff		
	0.07	0.01		
r (annual)		0.03		
Capex Δ		(1,456.00)		
Monthly CF		257.84	Monthly CF Δ	2.55
Yearly CF		3,094.11	Yearly CF Δ	30.63
0	(1,456.00)			
1	29.74	(1,426.26)		
2	28.88	(1,397.38)		
3	28.04	(1,369.35)		
4	27.22	(1,342.13)		
5	26.43	(1,315.70)		
6	25.66	(1,290.05)		
7	24.91	(1,265.14)		
8	24.18	(1,240.95)		
9	23.48	(1,217.47)		
10	22.80	(1,194.68)		
11	22.13	(1,172.55)		
12	21.49	(1,151.06)		
13	20.86	(1,130.20)		
14	20.25	(1,109.95)		
15	19.66	(1,090.28)		
16	19.09	(1,071.19)		
17	18.53	(1,052.66)		
18	17.99	(1,034.66)		
19	17.47	(1,017.19)		
20	16.96	(1,000.23)		
21	16.47	(983.76)		
22	15.99	(967.78)		
23	15.52	(952.25)		
24	15.07	(937.18)		
25	14.63	(922.55)		
No CAPEX Sum	533.45			
Sum w/ CAPEX	(922.55)	-3.9368% ROI		

Panel 2

	Cost	Eff		
	0.07	0.02		
r (annual)		0.03		
Capex Δ		(1,456.00)		
Monthly CF		260.40	Monthly CF Δ	5.11
Yearly CF		3,124.75	Yearly CF Δ	61.27
0	(1,456.00)			
1	59.49	(1,396.51)		
2	57.75	(1,338.76)		
3	56.07	(1,282.69)		
4	54.44	(1,228.25)		
5	52.85	(1,175.40)		
6	51.31	(1,124.09)		
7	49.82	(1,074.27)		
8	48.37	(1,025.91)		
9	46.96	(978.95)		
10	45.59	(933.36)		
11	44.26	(889.10)		
12	42.97	(846.12)		
13	41.72	(804.40)		
14	40.51	(763.89)		
15	39.33	(724.57)		
16	38.18	(686.39)		
17	37.07	(649.32)		
18	35.99	(613.33)		
19	34.94	(578.39)		
20	33.92	(544.46)		
21	32.94	(511.53)		
22	31.98	(479.55)		
23	31.04	(448.51)		
24	30.14	(418.37)		
25	29.26	(389.10)		
No CAPEX Sum	1,066.90			
Sum w/ CAPEX	(389.10)	-1.2361% ROI		

Panel 3

	Cost	Eff		
	0.07	0.03		
r (annual)		0.03		
Capex Δ		(1,456.00)		
Monthly CF		262.95	Monthly CF Δ	7.66
Yearly CF		3,155.38	Yearly CF Δ	91.90
0	(1,456.00)			
1	89.23	(1,366.77)		
2	86.63	(1,280.14)		
3	84.11	(1,196.04)		
4	81.66	(1,114.38)		
5	79.28	(1,035.10)		
6	76.97	(958.14)		
7	74.73	(883.41)		
8	72.55	(810.86)		
9	70.44	(740.42)		
10	68.39	(672.04)		
11	66.39	(605.64)		
12	64.46	(541.18)		
13	62.58	(478.60)		
14	60.76	(417.84)		
15	58.99	(358.85)		
16	57.27	(301.58)		
17	55.60	(245.98)		
18	53.98	(191.99)		
19	52.41	(139.58)		
20	50.89	(88.69)		
21	49.40	(39.29)		
22	47.96	8.67		
23	46.57	55.24		
24	45.21	100.45		
25	43.89	144.34		
No CAPEX Sum	1,600.34			
Sum w/ CAPEX	144.34	0.3788% ROI		

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